Glare Spot Phase Doppler Anemometry

Camille Hespel, Kuan Fang Ren, Gérard Gréhan, Fabrice R. A. Onofri

GLARE SPOT PHASE DOPPLER ANEMOMETRY

Hespel C*, Ren K F*, Gréhan G* and Onofri F†

*** UMR 6614/CORIA, CNRS - Université et INSA de Rouen, av. de l'Université, BP 12 76801 Saint Etienne du Rouvray, email : fang.ren@coria.fr**

† UMR 6595/IUSTI, CNRS-Université de Provence, Polytech' Marseille-DME, Technopôle Château-Gombert, 5 rue E. Fermi, 13453 Marseille

ABSTRACT

The Phase Doppler anemometry has been developed to measure simultaneously the velocity and the size of droplets. The measurement of the refractive index would be also interesting since it depends on the temperature and the composition of the particle and its measurement permits both to increase the quality of the diameter measurement and to obtain information on the temperature and/or the composition of the droplets. In this paper, we introduce a Glare Spot Phase Doppler Anemometry which uses two large beams. In this case, the images of the particle formed by the reflected and refracted light, known as glare spots, are separated in space. When a particle passes in the probe volume, the two parts in a signal obtained by a detector in forward direction are then separated in time. If two detectors are used the phase differences between two signals, the distance and the intensity ratio of reflected and refracted parts can be obtained and they provide rich information about the particle diameter and its refractive index, as well as its velocity. This paper is devoted to the numerical study of such a configuration with two theoretical models: geometrical optics and rigorous electromagnetism solution.

Key word: Phase Doppler anemometry, glare spot, particle imaging, refractive index, dual burst PDA

1. INTRODUCTION

In the research of two phase flow, the measurement of the velocity and the size of the droplets is essential. The Phase Doppler Anemometry (PDA) is one of the most important and the most used techniques to reach this end because it gives the correlation between the size and the velocity. But in certain circumstances, as in spray combustion or mixing, we need also to have access to the particle temperature/refractive index or mixing fraction.

With an elastic light scattering based technique such as PDA or rainbow refractometry, the only way to get information about the temperature or the material properties of a droplet or a particle is to measure its optical refractive index. The rainbow refractometry can measure precisely the refractive index (until 2.0 10^{-3} for nearly mono-dispersed droplets[1.]) and the mean refractive index for poly-dispersed clouds[2.]). But it does not give information about the velocity of the particle.

There exits also non elastic light scattering based techniques such as the Laser Induced Fluorescence (LIF) or Raman spectroscopy, to measure the temperature and particle composition. But theses diagnostics are quite difficult to implement. LIF, for example, based on the dependence of fluorescence spectra on the temperature but dye must be added in the droplets. The properties of fluorescence also depends strongly on the pressure and composition of the particles. Furthermore, those techniques require complementary methods to access to the particle size and diameter (such as PDA).

Then the *in situ* estimation of the refractive index of the scattering particles with the PDA measurement is a challenge to both increase the PDA size measurement accuracy and extract correlated information on the particle velocity, size, temperature and/or composition.

Different techniques have been developed[3.,4.] : extended PDA[3.,5.] , Dual Mode PDA[6.] , Dual Burst[7.8.] , coupling of PDA and rainbow refractometry[9.] , coupling of PDA and LIF[10.] which give velocity, size and refractive index of droplets. Among them, the Dual Burst technique is one of the more promising one. It is based on the temporal separation between the reflected and the refracted light of an individual particle thanks to a small probe volume formed by two strongly focused laser beams. So it imposes that the diameter of the particle must be of the same order or greater than the beam waist diameter and the measurement quality depends on the longitudinal location of the particles in the probe volume because of the strong curvature of the wave front.

To avoid the sensitivity to the wave front, we propose in this paper an innovative solution which is based on the separation of the light reflected and refracted by the particle in space[11.,12.] : two large beams are used to create the probe volume and the detectors are located in the image plane of the probe volume, in the forward direction at an angle where the intensities of reflection and of refraction of the first order are about at the same order. In fact, as the detector is located at the image plane, the signal is composed of two parts, one due to the reflection and the other due to the refraction.

This configuration, called Glare Spot phase Doppler anemometry (GS-PDA) will be studied by numerical simulation with geometrical optics model (GOM), which permits to understand the principle and treat the problem in a simple way, and with a full electromagnetic model (EIM) thanks to a simulation code of imaging of small particle. The sensitivity of GS-PDA to the refractive index and diameter of the particle will be examined in detail for different configurations.

The paper is organized as follows. A brief presentation of the glare spots and the GS-PDA configurations will be given in the section 2. The section 3 is devoted the geometrical optics model of GS-PDA. The full electromagnetic imaging model will be introduced and applied in the section 4 to investigate the possibility to measure the droplet refractive index and diameter. The conclusions are given in the last section.

2. GLARE SPOTS AND GS-PDA

When a particle is illuminated by a beam of light, it scatters the light in all space. If the particle is much larger than the wavelength of the incident beam we can observe distinctively at certain angle two bright points on the particle, which are called glare spots[13.] . The formation of the glare spots can be explained in a geometrical optics point of view as due to the separation of reflected and refracted light.

This principle can serve to separate the reflected and refracted light in particle measurements. We consider a particle of diameter *d* and refractive index *m* illuminated by a laser beam. The scattered light is collected by a lens of diameter ϕ and focal distance *f* located in the direction θ relative to the incident beam (Fig. 1). Two bright points are then formed on the image plan. One (*A*' in Fig. 1) is created by the refracted light and the other (*R*') by the reflected light.

When a particle is illuminated by two incident beams as in the classical Phase Doppler Anemometry (Fig. 2), the light due to the reflection and the refraction from the two beams interfere and form two spots on the image plane. When a particle passes in the probe volume, the detector(s) located on the image plane will produce a signal composed of two parts: one due to the reflection and the other due to the refraction.

The detailed analysis of such a configuration will be given in this paper by using the geometrical optics model (GOM) and the full electromagnetic imagine model (EIM) in the following sections.

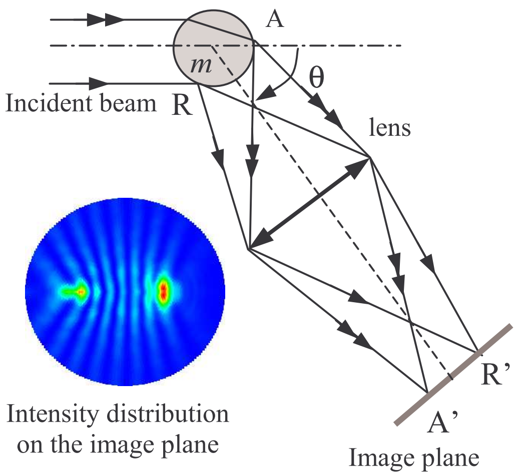

Fig. 1. Off-axis imaging and intensity distribution on the image plane

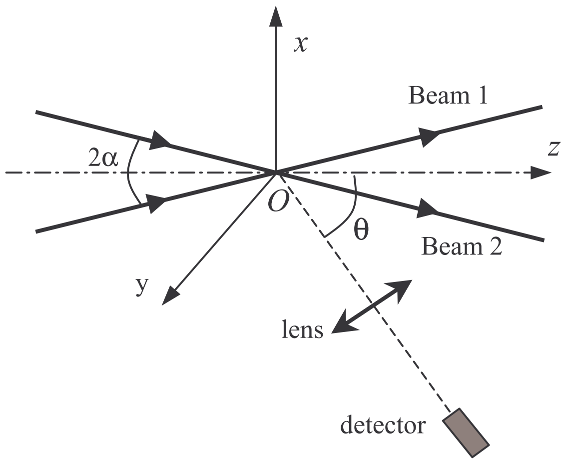

Fig. 2. Schema of a GS- PDA

3. GEOMETRICAL OPTICS MODEL

The geometrical optics is the most simple and instructive approach to understand the behavior of GS-PDA. At the first stage, we do not take into consideration the lens and the polarization of the incident wave.

When a particle of refractive index m and diameter d is illuminated by a plane wave of wavelength λ, the glare spots' positions can be determined by the refracted and reflected rays. The positions of the glare spots depend then on the refractive index, the diameter of the particle, and the detection angle θ. The detector being far from the particle, we suppose that the reflected and refracted rays are parallel for the simplicity.

For the convenience, we define the reference ray as the line coming from the source at infinity, passing by the centre of the particle and goes out in the direction of immerging rays (Fig. 3). The distances between the reference ray and the reflected or refracted ray is noted respectively by P_r, P_a (the subscript *r* and *a* represent respectively reflection and refraction). P_r and P_a are then given by:

$$P_r = \frac{d}{2}\cos\frac{\theta}{2} \qquad\qquad P_a = \frac{dm}{2}\sin\left(\frac{\theta}{2}\right)\Big/\sqrt{1+m^2-2m\cos\left(\frac{\theta}{2}\right)}$$

It is clear that the distance P_r is independent of the refractive index but P_a depends on the refractive index of the particle[14.-16.] . The distance between the two spots $D_s = P_r + P_a$ is proportional to the diameter and depends also on the refractive index and the collection angle. The intensities of the reflected and refracted light can be also calculated according to the geometrical optics[14.] .

When the particle is illuminated by two beams with an angle 2α between them, the reflected and refracted light from each beam interfere. The optical path differences for the reflected and refracted rays are proportional to the size of the particle, the intensities on the image plane for the reflection and the refraction are given by:

$$I_r = T_r d^2 \cos^2\left(\frac{A_r d}{2}\right) \qquad I_a = T_a d^2 \cos^2\left(\frac{A_a d}{2}\right)$$

where T_r and T_a are two coefficients depending on the reflection and refraction Fresnel coefficients and the optical configuration.

The figure 4 shows the behaviour of the reflected and refracted light intensities from a water droplet ($m = 1.33$) illuminated by two planes waves with a half-angle $\alpha = 5°$, the collection angle is $\theta = 66.5°$. The two factors A_r and A_a are respectively equal to $A_r = 0.299\pi$ and $A_a = 0.3533\pi$. The intensity of the spots varies periodically with the particle diameter. The corresponding periods are then 6.689 µm and 5.661 µm for reflection and refraction respectively.

This simple model of geometrical optics predicts the skeleton of the behaviour of the glare spots in the GS-PDA. The significant parameters as the lens dimension, the focal length, and the high order refraction effects have not been taken into account. These questions will be examined in the next section with a full electromagnetic model.

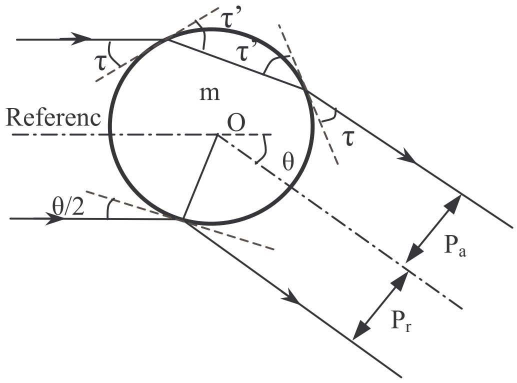

Fig. 3 Optical paths

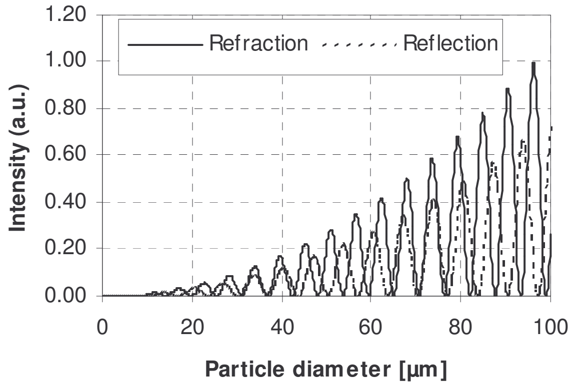

Fig. 4. Intensities as function of particle diameter predicted by geometrical optics.

4. ELECTROMAGNETIC IMAGING MODEL

In this section an electromagnetic imaging model based on full solution of Maxell's equations and Huygens-Fresnel diffraction principle will be used. The model will be presented in the first subsection and it will then be applied to one or two beam(s) configurations of a GS-PDA system.

The electromagnetic imaging model (EIM) is based on the work of Ren et al.[17, 18]. A particle of diameter d and refractive index m located arbitrarily in a laser beam of wavelength λ is considered. The calculation of the intensity on the image plane is composed of three steps. The scattered field on the surface of the lens is firstly calculated by the Lorenz-Mie theory or generalised Lorenz-Mie theory[19]. The role of the lens is then taken into account by the thin lens transformation[20]. The intensity on the detector is finally calculated by Huygens-Fresnel integration[21, 22, 17] of the electromagnetic field on the exit surface the lens.

4.1 Glare spots of a particle illuminated by one beam

When a particle is illuminated by one beam, two glare spots are formed on the image plane. Their intensities and the distance between them depend on properties of droplets (size and refractive index) and the optical configuration of the system.

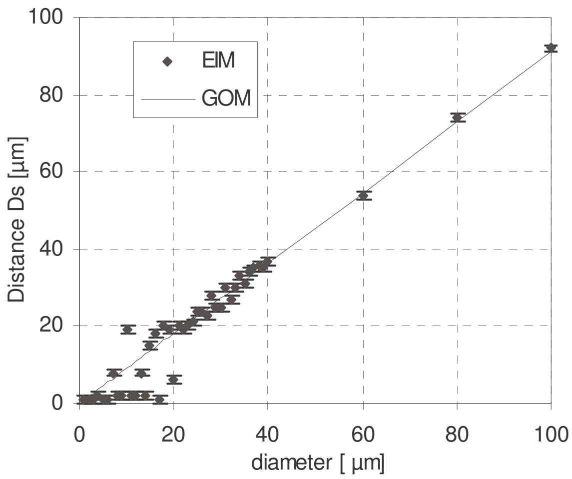

Fig. 5. Evolution of the spots' distance as function of the particle diameter.

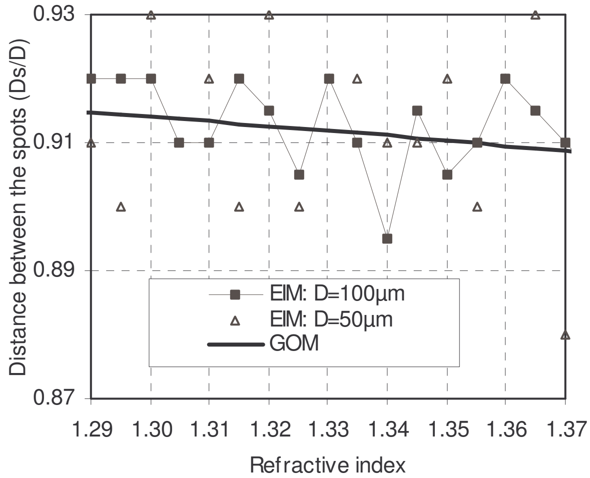

Fig. 6. Evolution of the spots' distance as function of the refractive index.

We consider a water droplet illuminated by a plane wave of wavelength 0.488 μm. The detector is located at $\theta = 66.875°$, on the image plane, 400 mm from the particle. The diameter and the focal length of the collection lens are respectively 15 mm and 200 mm. The magnification of this configuration is then equal to 1.

The evolutions of the maximum intensities and the distance between the spots due to reflection and refraction can be simulated by the full EIM. Fig. 5 shows the distance between the spots for a particle of refractive index 1.33. We find that when the diameter is greater than a critic value, about 20 μm in the present case,, the distance is proportional to the diameter of the particle and the agreement between EIM and GOM is rather good. So the distance between the spots can be used to determine the diameter of the particle. Figs. 6 displays the distance between the glare spots formed by reflection and refraction as function of the refractive index. The distance predicted by the EIM is in good agreement with GOM. The error is less than 1.0% for the particle of 100 μm and less than 5% for the particle of 50 μm.

4.2 Glare Spots Phase Doppler Anemometry

When the particle is illuminated by two beams, the total intensity on the detector is the sum of the electric fields scattered by the particle from the two beams. The two scattered fields then interfere on the detector. When a particle passes through the probe volume, the two spots' images pass successively the detector and the corresponding signals will be recorded. A typical GS-PDA signal simulated by EIM is presented in Fig. 7. A particle of 80 μm passes along *x* axis through the probe volume formed by two plane waves of wavelength 0.488 μm with a half angle of 5° between them (Fig. 2). The spacing in this configuration is equal to 2.8μm. The velocity of the particle is assumed to be 1.0 m/s and the period of the signal is then 2.8μs. The two parts due to the reflected and refracted light are well distinct in the signal. By the Fourier transformation we obtained the main frequency of the signal f=0.357 MHz. We can also obtained the pedestals of the signal by filtering the high frequency and extract the distance between the two spots and the intensity ratio. It is important to note that this signal is similar to the signals obtained by a dual burst PDA in which two tightly focalized beams are used [7,8].

The distance between the two spots and their intensity ratio as function of the particle size and its refractive index can then be extracted from this signal (Figs. 8 and 9). The detector in these simulations is located at θ = 67.574° so that the reflected and refracted light from a sphere of water (m=1.33) is of the same order of intensity.

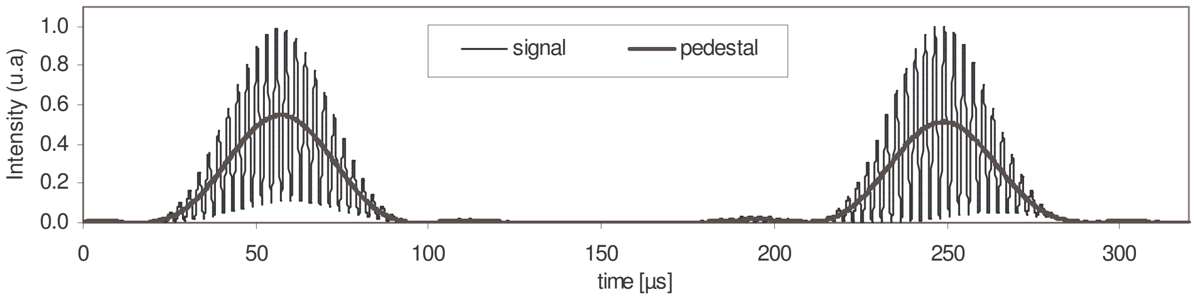

Fig. 7. Typical signal of GS-PDA

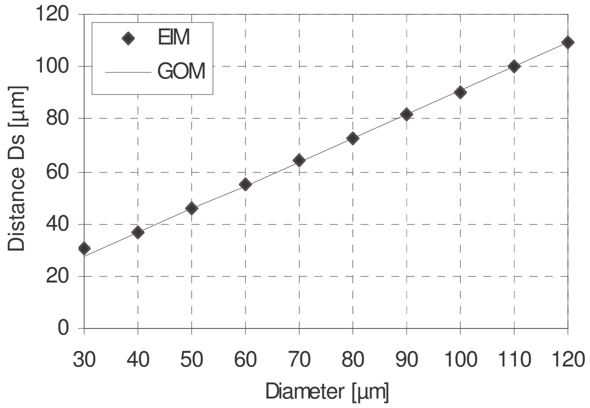

Fig. 8. Distance between the spots as function of diameter for a water droplet (m=1.33).

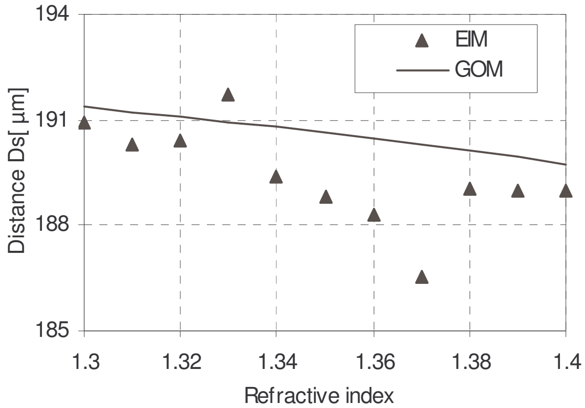

Fig. 9. Distance between the two spots as function of the refractive index for a water droplet (d= 80 μm)

When the particle moves in x direction, perpendicularly to the bisect of the two incident beams, the time delay between the two glare spots T_s is related to the displacement of the particle D_x and the distance between the spots D_s by:

$$D_s = D_x \cos\theta = V_x T_s \cos\theta$$

By taking into account this effect, the particle diameter can then be obtained from the time delay of the two spots provided that its refractive index and the direction of particle movement are known.

For the case shown in Fig. 7, the time delay between the two maxima in the pedestal is T_s=192 μs which corresponds to a displacement of D_x = 192 μm. Considering the angle position of the detector, the distance between the two spots D_s = 72.6 μm can then be deduced and it is in agreement with that predicted in Fig. 5.

In Fig. 8, the distances between the two spots D_s predicted by GOM and EIM are compared for a water droplet. The agreement is found very good. Therefore the distance D_s permits to determine precisely the diameter of the particle provided that the refractive index is known.

On the other hand, since the position of the refraction spot and the ratio of the two maximum intensities depend both also on the refractive index, we could expect to obtain information about refractive index from these values, if the diameter is known. Fig. 9 show the distance D_s as function of the refractive index for a water droplet of d = 80 µm. We find that the distances D_s depends little on the refractive index and the distance obtained from EIM signals is in general smaller than that obtained by GOM, but the difference is less than 2 %. Nevertheless, the fluctuation of the intensity ratio as function of the refractive index is too strong to be used to determine the refractive index by a linear relation.

When two detectors are used in GS-PDA, two signals will be obtained as in the dual burst PDA [7, 8]. Besides the distances D_s and intensity ratios as described above, we can also extract the two phase differences between the two signals separately for reflection and refraction parts.

Fig. 10 shows two signals simulated by EIM. We remark that the distances between the two intensity maxima are not the same because the two detectors are not symmetrical to the particle trajectory.

The phase differences extracted from the signals are shown in Fig. 11. We find that the phase differences are relatively stable around the maximum intensity and the average phase differences for reflection and refraction are respectively 43° and 24°.

It should be noted that the relation between the particle diameter and the phase differences is independent of the particle trajectory. It is therefore possible to determine the particle size and the two components of velocity by the distances between the spots and the phase differences between the two signals.

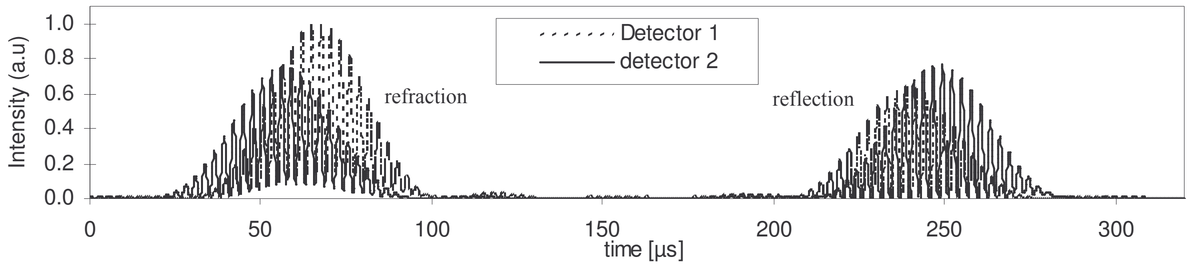

Fig. 10. GS-PDA signals obtained by two detectors located respectively at θ = 65.426° and 67.574° with a half angle of 5° for a water droplet (m=1.333, d=80 µm) illuminated by two plane wave of wavelength 0.488 µm.

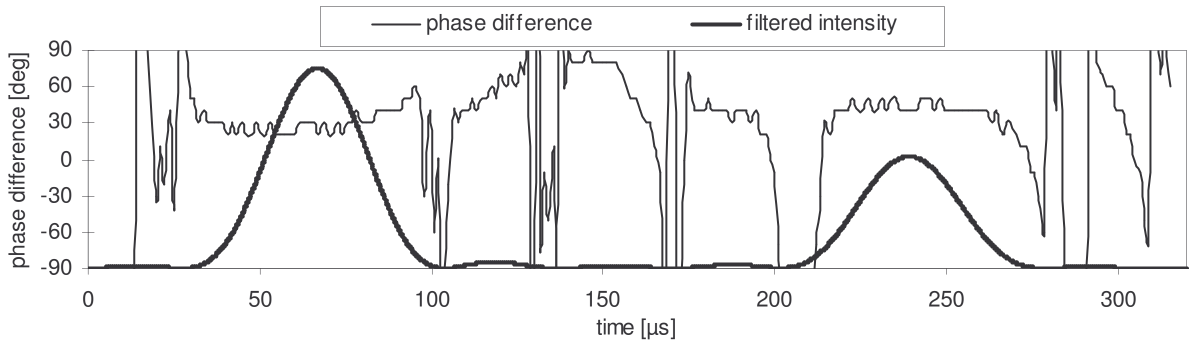

Fig. 11. Pedestal and phase difference between the two signals extracted from the signals in Fig. 11.

5. CONCLUSIONS

The principle of the Glare Spots Phase Doppler Anemometry is introduced and studied with a geometrical and a full electromagnetic imaging model. The GS-PDA uses two large beams and two detectors which are located on the image plane of the collection lens. The signals obtained with such system are composed of two parts in each of them: one due to reflection and the other to refraction. This new configuration provides richer information about the particle to be measured: two distances between the spots, two intensity ratios of the spots, two phase differences as well as the frequency of the signals can be extracted for the determination of the particle size and the refractive index as well as the two components of velocity. The particle diameter and two components of velocity could be determined by the spots' distances, the phase differences and the frequency of the signals if the refractive index is known. However the relation between the refractive index and the measured values (phase differences, spots distances and intensity ratios) are not linear in the planar configuration. The experimental validation is to be done and other configurations should be investigated for a real measurement of the diameter and the refractive index.

ACKNOWLEDGEMENTS

This work partially is supported by the inciting joint action, ACI "pollution, Non-pollution", VITAMA. project 47. This ACI is financed by the FNS, CNRS and the DGA.

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NOMINATURE

d diameter of a spherical particle
m refractive index of the particle
V velocity of the particle
α half-angle between the two incident beams
λ wavelength of the incident beam
θ angle between the bisect of the two incident beams and direction of the detector.
GS-PDA Glare Spots Phase Doppler Anemometry

Subscript

a refraction
r reflection